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EXPLOSION WELDING OF CYLINDRICAL SHAPES

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DEPARTMENT OF THE ARMY
FRANKFORD ARSENAL
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ABSTRACT

A number of papers have been published in the open literature on the explosion welding of concentric cylinders and on the joining of tubes to tubeplates. This paper attempts to provide a concise review of these contributions by discussing work performed by the authors and other investigators.

Basically, two explosion welding techniques have been employed to weld cylindrical members. These are the gap technique in which the walls of the members are positioned parallel to each other, and the angular technique in which the walls are inclined at an angle. In the present stage of process development, concentric cylinders generally are welded using the gap technique. Welding conditions and difficulties characteristic of the process are discussed.

Much of the available data on the explosion welding of cylindrical configurations relate to the joining of tubes to tubeplates. Both angular and gap techniques have been used for these applications. Advantages and disadvantages of these techniques are considered and a number of shortcomings that have been encountered are discussed. Various base metal combinations that have been used in explosively welded cylindrical specimens and tubes to tubeplate are reported.

INTRODUCTION

Explosion welding*, a relatively new process, is being considered and used for a number of specialized applications including the joining of cylindrically shaped components. This process is gaining increasing attention principally because of several significant features. Specifically, experience is indicating that the process can:

1. Join metals and alloys in various combinations and thicknesses which otherwise would be difficult if not impossible to weld.

2. Weld various materials without the need for external heating, extensive cleaning procedures, fluxing, gas shielding and the use of filler metals - all of which are often required in fusion welding operations.

3. Clad or weld large areas such as might be experienced in sandwich construction or in the inner or outer lining of cylinders.

4. Possibly be economically competitive, in some instances, with the more conventional fusion welding processes.

With this process, welding occurs when the adjacent surfaces of the materials to be joined are properly positioned and thrust together by energy released from an explosive source(1). As stated earlier, no external heating is normally introduced to the welding operation although some heat is generated at the weld interface because of the absorption of energy(2).

The explosion welding process is gaining the attention of both design and fabrication engineers particularly for joining cylindrically shaped components. Several welding procedures and a number of applications have been reported(1 to 13). The applications include the cladding of tubes for reactors, the lining of half cylinders for turbine engine applications, cladding of cylinder bores and pistons, welding of pipes and tubing of dissimilar materials for aerospace, cryogenic and reactor applications and the cladding of pressure and mixing vessels for the chemical and petroleum industries. Also, increasing attention is being given to the welding of tubes to tubeplates for heat exchanger applications. It is intended that this paper review the work of the authors and others concerning explosion welding theory and application to cylindrically shaped items.

*Explosion Welding is the official designation given this process by the American Welding Society.

(1) Superscripts refer to references at end of paper

THEORY

Two basic conditions must be satisfied in order for welding to occur with any joining process. First, the surface of the materials being welded must be relatively free of surface films. These films are usually composed of oxides, nitrides or absorbed gases. When any of these films are present, they can prevent satisfactory joining. Second, the materials being joined must be brought into such close proximity that their atoms establish a bond through interatomic forces.

These conditions can be satisfied by the explosion welding process. It is generally agreed that surface films are removed by a phenomenon known as jetting[9-10, 13-17] and that the clean surfaces are brought into contact by high pressures (up to several million pounds per square inch) generated by the explosive charge. In considering the explosive charge, its detonation rate will be either subsonic or supersonic with regard to the velocity of sound in the materials being joined. Explosives in either category, however, can be used under certain controlled conditions that will permit the formation of an effective jet.

Welding Conditions for Obtaining Jetting with Subsonic Detonation Rate Explosives

In Figure 1, the welding of two concentric cylinders* is illustrated at some small increment of time after detonation of the explosive charge has initiated. For the purpose of illustration, only the top cross-section of Figure 1A identifies the parameters entering into the explosion welding operation. However, because of the symmetry of this particular operation, the analysis applies completely around the cylindrical components. The variables shown in the figure are as follows:

x = gap or original distance between concentric members

V_d = detonation velocity of the explosive

V_{cp} = collision point velocity or velocity at which the point of collision moves along weld interface.

V_i = impact velocity of inner cylinder if the decrease in velocity due to expansion is neglected.

In forming the weld, surface films moving along with a thin layer of metal from the unwelded portion of the members being joined combine at the point of collision to form a jet. However, for this phenomenon to occur effectively two conditions must be met. First, the collision point velocity (V_{cp}), generally ranges from about 47,000 in/sec[11] up to the speed of sound in the members being joined. Second, the impact velocity, V_i, must

*In this example, both members are hollow right cylinders.

be greater than the minimum value required to produce pressure sufficient to overcome the elastic strength of at least one of the members. When these conditions are met, sufficient pressure will be produced ahead of the collision point to cause metal flow in two directions. If one could be at the point of collision, these two "streams" of material would appear to move in opposite directions. The minor stream forming the jet, would move in the direction of detonation. The major stream would comprise that material forming the weldment as it moves in the opposite direction to that of detonation.

The variables in Figure 1A may be estimated from a combination of theoretical considerations and past experience. In this setup, a uniform spacing often called the gap, x, is provided between the two cylinders before detonation. The minimum gap distance in which the inner cylinder can reach its equilibrium velocity usually is not greater than the thickness of the inner cylinder(16). The detonation velocity of the explosive is a function of the density and thickness of the charge and can be estimated from equations readily available in the literature or obtained from well known experimental methods such as the pin contact technique(17 & 18).

The collision point velocity, V_{cp}, is equal to the detonation rate of the explosive charge in the configuration shown in Figure 1A due to geometrical considerations. The impact velocity can be estimated from the following equation(3):

$$V_i = V_d \frac{(0.578 \frac{c}{m})}{2 + c/m} \qquad \text{eq. (1)}$$

where

c = mass of explosive, and

m = mass of inner cylinder

In this equation, V_i is an equilibrium velocity and is obtained only if the gap distance is sufficient for this velocity to be reached.

When the impact velocity is known, the impact pressure (P_i) may be estimated according to(3):

$$P_i = \tfrac{1}{2} V_i V_s \rho \qquad \text{eq. (2)}$$

where

V_i = impact velocity of inner cylinder if the decrease in velocity due to expansion is neglected.

V_s = velocity of shock in inner cylinder.

ρ = density of inner cylinder.

Welding Conditions for Obtaining Jetting with Supersonic Detonation Rate Explosives

When the charge detonation rate, V_d, and hence the collision point velocity (V_{cp}), is greater than the speed of sound in the materials being welded, oblique shock waves can form at the collision point. This can prevent the jetting phenomenon and its attendant beneficial cleaning action at the joint interface. Hence oxides and other surface materials are not removed and no bond is accomplished. However, if the impact velocity, V_i, can be made to exceed a certain critical value, the oblique shock waves will detach from the collision region, move upstream, and form a pressure distribution pattern that will permit a jet to form and remove the surface contaminants. The value of this critical velocity differs from system to system and can be found either empirically or estimated from the method given by Chudzik[10]. Care must be taken, however, to insure that the greater amount of explosive needed to exceed the critical value of V_i does not result in fracturing the cylinders.

Satisfactory weldments can not be obtained with this particular procedure, even when jetting is present, if V_{cp} exceeds 120 percent of the speed of sound in the materials[11]. In order to obtain jetting under these conditions, the quantity of explosive required for an adequate impact velocity, V_i, must be so high that the assembly will usually deform, fracture or exhibit spalling.

There are, however, several methods by which an explosive whose detonation rate is considerably greater than the speed of sound in the materials being welded may be used with the gap technique.

In one method, the detonation velocity of an explosive may be reduced along the longitudinal axis of two cylinders by appropriately spiraling the explosive. Thus the "effective" detonation rate of the explosive can be made less than the speed of sound in the materials being welded.

A tapered buffer between the charge and the inner cylinder may also be employed with concentric members when using an explosive having a detonation rate appreciably greater than the sonic velocities in the materials being welded. Materials such as rubber and plastic have low sonic velocities. Therefore, if these materials are tapered and used as a buffer, there will be an increasing delay in time between detonation and the succeeding portions of the inner cylinder impacting the outer cylinder. Thus, the collision point velocity may be made subsonic and, with the proper impact velocity, a bond will be accomplished.

However, the most convenient welding technique for bonding cylinders with supersonic detonation rate explosives employs an angle between the walls of the members (See Figure 1B).

This technique usually is restricted to applications where relatively short lengths are to be welded. If used with joints of moderate length or greater, fracturing generally occurs due to excessive stretching in one of the members.

Based on background information provided by Wright et al[13], the authors developed the following equation which relates the various welding parameters to the minimum angle α (See Figure 1B) needed to produce a weld.

$$\alpha = \sin^{-1} \frac{V_i'}{2V_s V_d} \sqrt{4V_d^2 - V_i'^2} - 2\sin^{-1} \frac{V_i'}{2V_d} \qquad \text{eq. (3)}$$

In equation (3), V_i' which is the impact velocity takes into account deceleration of the inner cylinder due to deformation. V_i' may be calculated from the equation[8].

$$V_i' = \sqrt{V_i^2 - \frac{4\, y\, L \tan \alpha}{\rho D}} \qquad \text{eq. (4)}$$

where y = dynamic yield strength of inner cylinder

L = distance of an elemental ring from beginning of taper

D = inside diameter of inner cylinder

ρ = density of inner cylinder

V_i = impact velocity where deformation energy is negligible as when two flat panels are welded together.

Accordingly, equations (1), (3), and (4) may be used to calculate α if the ratio of the mass of the explosive to the mass of the inner cylinder (c/m) is known. This is done by using c/m to calculate V_i from eq. (1). Since ρ and D are known, V_i and various values of L are then used to calculate values of V_i' from eq. 4. The values of V_i' are substituted in eq. 3 to get various values of α. This equation and other equations [8] show that the taper angle usually is small, about 2 degrees in many instances. Several variations of this method which have been used to weld tube to tubeplate will be discussed later.

EXPLOSION WELDING OF CYLINDERS

Limited information has been published in the open literature on procedures for explosion welding concentric cylinders or cylindrical components along their parallel walls. This is probably due as much to a general lack of knowledge concerning the relationship among the basic welding variables as to the desire to protect proprietary information.

Most of the information presented in this section is the result of work conducted by the authors. The welding methods were developed on

relatively small members but are believed applicable, within limits, to the welding of large cylinders.

Procedure for Welding Concentric Cylinders

In recent work, the authors conducted feasibility studies for lining the interior of hollow chrome-moly-vanadium steel cylinders with 0.010 inch thick T111 tantalum alloy liners. The cylinders had a 0.6 inch ID, a 7/16 inch wall and were 4 inches long. The cylinder material had been heat treated to provide an approximate hardness of 300 Brinell. The tantalum liners had been cold drawn and stress relieved to also gain a hardness of about 300 Brinell. Ranges in chemical composition of the cylinders and liners are given in Table 1.

In preliminary experiments for developing a welding procedure having application to concentric cylinders, flat tantalum alloy T111 panels and 4150 steel bars were used to minimize labor and material costs. Alloy steel 4150 was employed due to its similarity in chemical composition to the chrome-moly-vanadium steel and its immediate availability for the experiment. The tantalum members were 0.010 inch thick by ½ inch wide by 4 inches long and the 4150 steel members were ½ inch thick by 0.4 inches wide by 4 inches long. The hardness characteristics of these materials were similar to those of the cylindrical components. The chemical composition of the 4150 material also is given in Table 1.

The gap technique was employed with the flat components since the objective was to obtain a set of conditions applicable to the welding of the concentric cylinders. Angular orientation could not be used on the concentric members because it would require the inner cylinder to be tapered. This would not be practical since the 0.010 inch thick tantalum cylinder would fracture during welding from excessive stretching.

Welding of the flat components was accomplished in air using nitroguanidine as the explosive. The influence of explosive density, charge thickness and gap distance on weld quality was determined in order to gain information that could be used as a basis for welding the cylinders. The most promising welding procedure as indicated by mechanical tests and metallographic examination was obtained with a ½ inch thick charge having a density of 0.4g/cc. The nominal gap distance was 0.05 inches. Tensile, hardness and peel tests were used to evaluate the mechanical properties of the assemblies.

The welded flat assemblies when peel tested, failed by fracturing through the tantalum member. These peel tests also indicated that the edges of the specimen were not welded. This was probably caused by a reduced pressure pulse above this region resulting from the dissipation of detonation products. The lack of welding at the edges, however, was not considered a problem since only the conditions along the longitudinal centerline of the flat assemblies would be encountered in the welding of cylinders. The strength of the weld as indicated by tensile tests was found to be approximately 23,400 psi. Since bending stresses were experienced during testing due to the design of the specimens, slight rotation occurred. It is likely, therefore, that unidirectional loading of the

specimens would have resulted in a significantly higher strength value. Failure occurred essentially in the tantalum alloy which comprised more than 90 percent of the fractured interface. Metallographic examination showed that the weld interface was well bonded. Also, a hardness survey across the interface indicated that the base metals were not hardened significantly by the welding operation.

In view of these results, the experiments were extended to cladding the interior of the smooth walled hollow steel cylinders with the T111 tantalum alloy liners. The welding setups employed are given in Table 2 and shown in Figures 2 and 3.

A welding setup in which spacers were used between the tantalum liner and steel cylinder is shown schematically in Figure 2A. The spacers, cylinder and liner are shown in Figure 2B.

The anvil and cylinder were connected by Cerrobend (Figure 2A) a low melting eutectic alloy of bismuth, in order to insure the dissipation of shock waves and excess energy. After the welding operation, the Cerrobend was heated to its melting point (158°F) and the welded assembly was retrieved. In some tests, however, the anvil ring was not used. Welding was conducted in air and also in a partial vacuum of about 3 cm of Hg.

Another setup employed the spacers outside the steel cylinder as illustrated in Figure 3A. The relative size of the spacers, liner and cylinder may be observed in Figure 3B.

The most promising procedure employed the setup using external cylinder positioners (Figures 3A and 3B). A photograph of the sectioned specimen made with this procedure is shown in Figure 4. Metallographic examination indicated that the tantalum tubing was welded along the length of the cylinder except for its peripheral edges. Typical views of the welded interface are shown in Figures 5A and 5B. The interface exhibited a wavy pattern characteristic of explosively welded joints. Intermittent interfacial layers of varying length and thickness also were noted. The layers were similar to structures observed in flat explosively welded assemblies and identified as being composed primarily of tantalum and iron with traces of tungsten.

The adherence of the liner to the cylinder was demonstrated by bend and peel tests. A 0.047 inch thick by ¼ inch wide longitudinal bend specimen was fabricated from the welded assembly and bent, with the liner side in tension, around a 5/16 inch mandrel. A 67 degree bend was accomplished before cracking occurred. The crack extended through the tantalum across the weld interface and into the steel member as shown in Figure 6A. A peel test confirmed that the interior surface of the cylinder except for its ends had been clad. The unbonded zone varied in length from 0.050 to 0.2 inches as shown in the left hand specimen of Figure 6B.

It was determined that the amount of nonbonding at the edges of the cylinder was dependent on the type of positioning method employed. When the "inside positioner" (Figure 2A) was used, the impact velocity of the tubing was reduced to the extent that gross nonbonded areas occurred as shown in the right hend specimen of Figure 6B.

In this specimen, the unbonded zone at the edges varied in length from 0.25 inch to 1 inch.

It was also determined that welding could be accomplished without experiencing significant plastic radial expansion in the outer cylinder. No appreciable expansion was noted regardless of whether an anvil ring was employed or whether an atmospheric environment or partial vacuum was used. Other investigators, however, have reported that cylinders of different material and thickness combinations were detrimentally deformed when anvil rings were not used. It would appear, therefore, that the need for an anvil ring may depend on the base metals and thickness involved. No attempt was made by the authors to measure the radial expansion of the tantalum liner.

The collision point and impact velocities as well as the impact pressure generated by the tantalum alloy liner were calculated for the best welding conditions using the previously discussed theoretical equations. In these calculations, the value of c/m was 0.29. The calculated detonation velocity* and hence collision point velocity was 120,000 inch/sec. Making the appropriate substitutions in equation (1), the impact velocity was then found to be 8800 inches/sec. Knowing that the density and sonic velocity of the liner were 0.604 pounds/inch^3 and 134,000 inches/sec, the impact pressure according to equation (2) was 924,000 pounds/inch^2.

<u>Other Procedures for Explosion Welding Cylinders</u>

It was previously pointed out that explosives with detonation velocities between 100 and 120 percent of the sonic velocity may be used with the gap technique provided the impact velocity is sufficiently high. This method has been employed by Cowan et al[11]. A right cylinder having a 1 inch overlap was formed by wrapping a 6 inch by 10 inch by 0.008 inch sheet of titanium around a steel mandrel. The gap was provided in the overlapped region by employing projections in the sheet. A strong, sound joint was produced with a specially prepared sheet explosive composed of 35% PETN, 50% red lead and 15% butyl rubber-terpene resin binder. The detonation velocity was approximately 105 percent of the sonic velocity of the base metal.

Explosives in cord form also have been used to clad hollow cylinders[12]. Cord explosives were positioned inside the liner to form a lattice network. Welding apparently did not occur throughout the entire interface but only near the cord. The method has been used to clad the interior of soft steel pipe with stainless steel. Less explosive is used with this method than with other methods that would weld the entire interface. Also, a uniform gap or parallel distance between base metals is not required.

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*V_d = 1445 + 4015e for Nitroguanidine[19]

where V_d = detonation velocity in m/sec

and e = density of charge in g/cc

Large diameter hollow steel cylinders clad by explosion welding usually have been made from flat steel plate. With this method, the plate is explosively clad, rolled into a cylinder and joined along the longitudinal seam by fusion welding. Both the angular and gap techniques have been used. The explosives were in sheet and cord form.

Base Metal Combinations Welded as Concentric Cylinders

A number of material combinations that reportedly have been explosion welded into cylindrical components are given in Table 3. The list is not all inclusive but does cover the more widely publicized base metal combinations used.

WELDING OF TUBES TO TUBEPLATES

A promising application for the explosion welding process is the joining of tubes to tubeplates for heat exchangers as shown in Figure 7[4]. An extensive amount of experimental work on tube to tubeplate applications has exhibited so much potential that the components for several commercial heat exchangers have been welded with this process.

The conventional methods of joining tubes to tubeplates are usually fusion welding and roll bonding. Unfortunately, both methods have certain disadvantages particularly when dissimilar metal combinations are involved. In regard to fusion welding, cracking can be encountered at the weld interface of bi-metal combinations because of the formation of brittle intermetallic compounds and differences in base metal thermal expansion. Also, the base metal strength of some similar and dissimilar combinations can be detrimentally affected by heat input. The heating requirements of the fusion welding process tend to destroy the effect of prior heat treatment and cold work. Many of these base metal combinations, however, reportedly have been explosion welded without experiencing cracking or a lowering of base metal strength.

With respect to roll bonded joints, the mechanically expanded tube to tubeplate joint has been reported to be unsatisfactory for an increasing number of applications[5]. Explosion welded joints in one study exhibited significantly higher properties than similarly tested roll bonded joints imposed to test conditions which were severe compared to those normally encountered in service.

Techniques Employing Subsonic Detonation Rate Explosives

In explosion welding of tubes to tubeplates, a relatively simple setup has been used with explosives having detonation rates below the sonic velocity of the base metals. This is shown in Figure 8[4]. The base of the hole as shown in the figure is drilled so that there is a snug fit between the tube and the tubeplate for a short distance to align the tube. The remainder of the hole is drilled oversize to provide a suitable gap between the tube and tubeplate. Since the tube wall is parallel to the wall of the plate, the collision point velocity, which is equal to the detonation rate of the explosive will be subsonic. This technique may also be used with

some modifications such as drilling the tube hole oversize completely through the plate and relying on the use of suitable spacers for positioning the charge. A bond will be accomplished provided the diameter of the charge is large enough to sustain detonation and a sufficient impact velocity is imparted to the inner member.

Explosive packs, (inserts containing a prepackaged charge), have been used to weld tube to tubeplates (See Figures 9[4] and 10[4]). Although not shown in these figures, some packs have been made with positioning legs that fit against the face of the tube plate and permit the charge to be aligned quickly and accurately. The charge in Figure 9 has been used to weld individual tubes to tubeplates. If a number of tubes are welded simultaneously, a reliable detonation firing circuit must be employed to prevent misfires or one or more premature firings could knock out of position or destroy the other charges and tubes and prevent welding. The pack in Figure 10 is designed to eliminate this problem. The essential difference between this pack and the previous one shown in Figure 9 is that it employs a length of cord explosive as a fuse. To weld a number of tubes to a tubeplate simultaneously, equal lengths of detonation cord from a number of packs were initiated by a single detonator. However, this technique must be used with caution since the use of several lengths of cord may result in excessive blast in the immediate area of the tubeplate.

Techniques Employing Supersonic Detonation Rate Explosives

Explosion welding methods also have been developed for joining tubes to tubeplate when using explosives having a detonation rate higher than the speed of sound in the base metals. These are illustrated in Figures 11[3] and 12[4]. The method in Figure 11 employs a hollow tapered cylinder to strike the tubing in such a manner that the collision point velocity between the tubing and tubeplate will be subsonic. The impact velocity of the tapered cylinder is usually appreciably greater than that required to weld the tubing because only part of its velocity will be imparted to the tubing. This technique reportedly[3] has been employed to weld stainless steel tubing to stainless steel tubeplate using a lead cone. The lead was not welded to the tubing because its sonic velocity was much less than that of the stainless steel. If the cone and tubing had been made of the same material, a layer of grease could have been used to prevent them from being welded. Parallel members may be welded also by tapering the energy transmitting medium (Figure 12) as previously discussed.

Although these two welding methods are accomplished with the gap technique, it is generally more convenient to employ an angle between the tube and tubeplate when using a high velocity charge. The purpose of the angle is to reduce the collision point velocity of the members to less than their sonic velocities. Typical setups that employ angular orientation are shown in Figures 13A to 13D.

The minimum taper angle to obtain a subsonic collision point velocity for the geometrical setup shown in Figure 13A[3] may be calculated from equations 3 and 4. The following illustration shows how these equations may be used for this purpose. Consider that a T111 tantalum alloy tubing, ½ inch in OD with a 0.010 inch wall is to be welded to a 2 inch thick steel tubeplate having a taper hole 1.5 inches in length. The density of the

tubing is 0.604 pounds/inch^3. Its dynamic yield strength may be taken as six times the static yield strength[17] or 600,000 pounds/inch^2. The impact velocity, V_i, of the tubing, neglecting deformation may be taken as 8800 inches/sec since this value apparently produced a weld in the concentric cylinder study. Furthermore, if the explosive charge is Primacord, the detonation rate is 300,000 inches/sec, a value appreciably greater than the sonic velocity of tantalum (Approx. 134,000 inches/sec).

Using the above data, the relation between the taper angle and the taper length were determined with equations 3 and 4. Results of the calculations are shown in Table 4. The minimum angle to produce welding was about two degrees and five minutes regardless of whether deformation was or was not taken into account. Furthermore, the impact velocity was reduced only slightly. These results indicate that the energy of deformation in this instance was not significant.

According to Chadwick et al[8], however, the calculated angles generally range between ½ and 2 degrees decreasing with distance from the beginning of the taper. To simplify the machining operation, a hole having a constant taper is used in practice. The taper usually is chosen to be greater than the minimum for most of the tubehole length. Also the clearance between the tube and wall of the tubeplate should be sufficient to permit an adequate impact velocity to be achieved.

The welding method shown in Figure 13A may be employed where the pitch (spacing) between holes in the tubeplate is not critical with respect to distortion. The setups in Figures 13B[4] and 13C[4] which have the angle machined into the tube wall are similar in principle to the tapered tubeplate method. Both setups allow smaller pitches to be used because less explosive is needed to achieve the proper impact velocity due to the decreased mass of tubing.

The two setups, however, differ in that the detonator is positioned inside the tubing in one technique whereas the other employs external detonation. The technique employing internal detonation permits welding essentially throughout the joint. In contrast, no welding takes place at the edge of the joint when external detonation is used. This region is not welded because the gap distance is too small for the tubing to obtain a sufficient impacting velocity.

When the pitch is too small to use the tapered tubeplate method and the tubing too thin to machine into an angle, an angle may be introduced by forming the tube as shown in Figure 13D[3].

Another method that may be employed to bond tubes to tubeplates utilizes a machined taper on the inside of the tubing[4] as shown in Figure 14. The reduced collision point velocity is achieved by adjusting the taper of the tubing. The impact velocity decreases as detonation progresses into the tubeplate because c/m decreases with increasing thickness of tubing. An equation that may be used as a first approximation for calculating the minimum taper angle has been developed by Chadwick[3].

Properties of Joints Between Tube and Tubeplate

Explosively welded joints between tubes and tubeplates have exhibited a high degree of integrity when mechanically tested and metallographically examined. Mechanical test methods have included peel, push, tensile and fatigue tests. When satisfactory welded assemblies were sectioned along their longitudinal axis and peel tested, fracture generally occurred in the tubing adjacent to the welded region. Attempts to conduct push tests by pushing the tubes through tubeplates resulted in buckling of the tubes. When tensile shear specimens were removed from the welded assemblies and tested, fracture usually occurred through the base metal adjacent to the weld. It has been reported that explosion welded joints subjected to fatigue tests[8] or thermal cycling[5 & 8] performed significantly better than similarly tested joints in assemblies mechanically swaged together.

Metallographic examination by a number of investigators indicated that the weld interfaces were sound and had the structural characteristics associated with this process, i.e., severely distorted grains and straight zones relatively free of plastic deformation. Small amounts of localized melting also have been noted at the interface. The extent and location of the welded area apparently depended largely on the configuration of the joint. As an example, it was previously pointed out that in the setups shown in Figures 13B and 13C, the one employing internal detonation (Figure 13B) produced a weld having a greater proportion of its edges bonded.

Precautions for Minimizing Tubeplate Damage

Investigations[4] have shown that the distortion of the tubeplate must be taken into account when welding tubes to tubeplate. When the tubes are welded individually or in batches, radial expansion of the remaining holes must be considered or the unwelded holes in the tubeplate may become so distorted that insufficient gap is left for the welding of subsequent tubes. The work also indicated that less plastic deformation was produced in the tubeplate when tubes were welded simultaneously instead of individually.

In regard to other work on distortion, Chadwick et al[8] reported that stress corrosion cracking can occur in certain explosion welded tube to tubeplate combinations. The problem was easily eliminated through stress relieving the outer surface of the joint by peening. It was also reported that slight bowing has been observed in explosion welded tubeplates. In one industrial installation, for example, 3/4 inch diameter by 0.035 inch thick tubes were welded into a 6 foot diameter tubeplate, 1½ inches thick. The welding operation plastically deformed the outer surface of the tubeplate into a convex shape having a maximum bulge height of ¼ inch. However, no stress corrosion cracking problem was associated with this condition.

Studies[4] have demonstrated that tubes can be damaged by debris from an improperly positioned charge. Also, tube damage may be caused by a charge positioned too near to the rear of the tubeplate. These problems may be eliminated by using hardened steel rings to protect unwelded tubing from debris and by incorporating protuberances in the explosive pack to correctly locate the charge in the tube hole.

Base Materials

In joining tubes to tubeplates, various metals and alloys have been welded as shown in Table 3. Both gap and angular techniques are represented in the welding of these materials. Generally, the gap technique was used with subsonic detonation rate explosives whereas the angular technique was employed with supersonic detonation rate explosives.

Fabrication Rates

It would appear that most heat exchangers fabricated by this process were made by welding individual tubes to tubeplate. Chadwick et al[8] reported that a maximum firing rate of 120 welds per hour has been achieved but that the average firing rate was closer to 55 joints per hour. The percentage of acceptable welds fabricated at four installations ranged from 98 percent to more than 99.5 percent.

Work also has been conducted on an experimental basis with simultaneous firings of multiple charges[8]. The maximum firing rate was approximately 130 welds per hour. During the test, ten (10) tubes were welded simultaneously for each firing. When the operator attempted to fire more than 50 welds simultaneously, however, the increased effort expended to avoid misfires reduced the firing rate. However, the development of improved multiple firing techniques could lead to higher production rates.

Related Applications

The procedure used for heat exchangers may be applied with some modification to the welding of similar items such as tubular transition joints. The modifications are associated principally with the use of the anvil as a die or mandrel. To weld a tubular member to the interior surface of a hollow cylinder, the explosive may be placed inside the tube and a die positioned outside the cylinder. Conversely, the outer surface of a hollow cylinder may be clad with tubing by placing the explosive around the exterior of the tubing and a mandrel inside the tubing. The die and mandrel serve as an energy sink and aid in maintaining the dimensions of the cylinder.

CONCLUSIONS

It may be concluded that:

1. Cylindrical components such as concentric cylinders, tubular transition joints and tubes to tubeplate can be explosion welded. Large diameter clad cylinders have been made by forming explosively clad sheet or plate into the cylindrical shape and subsequently welding the seam by one of the fusion welding processes.

2. Explosion welding can join many similar and dissimilar material combinations, many of which are often difficult, if not impossible, to weld by the fusion welding processes.

3. A number of explosion welding methods have been developed for cylindrical shapes. The appropriate method depends on the configuration and dimensions of the components to be joined as well as the detonation rate of the explosive charge.

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TABLE 1 - CHEMICAL COMPOSITION

Alloy	Elements - Weight[a] Percent								
	W	Hf	C	O_2	N_2	Fe	Ta		
Tantalum alloy T111	7/9	1.5/2.5	.005 nom	.010 nom	.005 nom	.005 nom	rem		
	C	Mn	P	S	Si	Cr	Mo	V	Fe
Chrome-moly vanadium steel	.41/.49	.60/.90	.040 max	.040 max	.20/.35	.80/1.15	.30/.40	.20/.30	rem
4150 steel	.48/.55	.75/1.00	.040 max	.040 max	.20/.35	.80/1.10	0.15/0.25	—	rem

a - Single values are either nominal or maximum percentages

TABLE 2 - WELDING CONDITIONS FOR CYLINDERS

Outer cylinder	- 0.6 in. ID chrome-moly-vanadium steel cylinder, 7/16 in. thick by 4 in. long
Inner cylinder	- 0.5 in. OD T111 tantalum tubing, 0.010 in. thick by 5 in. long
Explosive charge	- 0.4g/cc nitroguanidine, 0.480 in. OD
Gap	- 0.05 in.

Enviromental Medium	Location of Spacers	Remarks
Partial vacuum	Between liner and cylinder	Anvil ring used
Partial vacuum	Between liner and cylinder	No anvil ring used
Air	Between liner and cylinder	No anvil ring used
Air	Surrounds cylinder	No anvil ring used

TABLE 3 - BASE METAL COMBINATIONS USED IN EXPLOSION WELDED CYLINDRICAL COMPONENTS

TUBING	TUBEPLATE OR CYLINDER														
	Aluminum Brass	Naval Brass	Muntz Metal	Aluminum Bronze	90/10 Cupro Nickel	70/30 Cupro Nickel	Copper	Magnesium	Mild Steel	Cr-Mo-V Steel	A212B Steel	A285B Steel	Stainless Steel	Titanium	Zircaloy
Aluminum								B	B				A,B	B	B
Aluminum Brass	A	A	A	A	A	A			A				A		
70/30 Brass		A	A												
90/10 Cupro Nickel		A			A	A			A						
70/30 Cupro Nickel		A				A			A						
Copper		A					A		A						
Inconel									A						B
Nickel												B			
Mild Steel				A					A				B		
Stainless Steel									A,B				A		B
T111 Tantalum										B					
Titanium									A				A	A,B	
35 A Titanium											B				

Key: A - Tube to Tubeplate
B - Other Cylindrical Shapes

TABLE 4 - RELATIONSHIP AMONG LENGTH OF TAPER, TAPER ANGLE AND TUBING IMPACT VELOCITY

Length of Tubehole (in.)	Taper Angle (deg and min)	Impact Velocity of Tubing (in./sec)
0	2° 5.04'	8,800
0.5	2° 4.92'	8,791
1.0	2° 4.80'	8,783
1.5	2° 4.68'	8,774

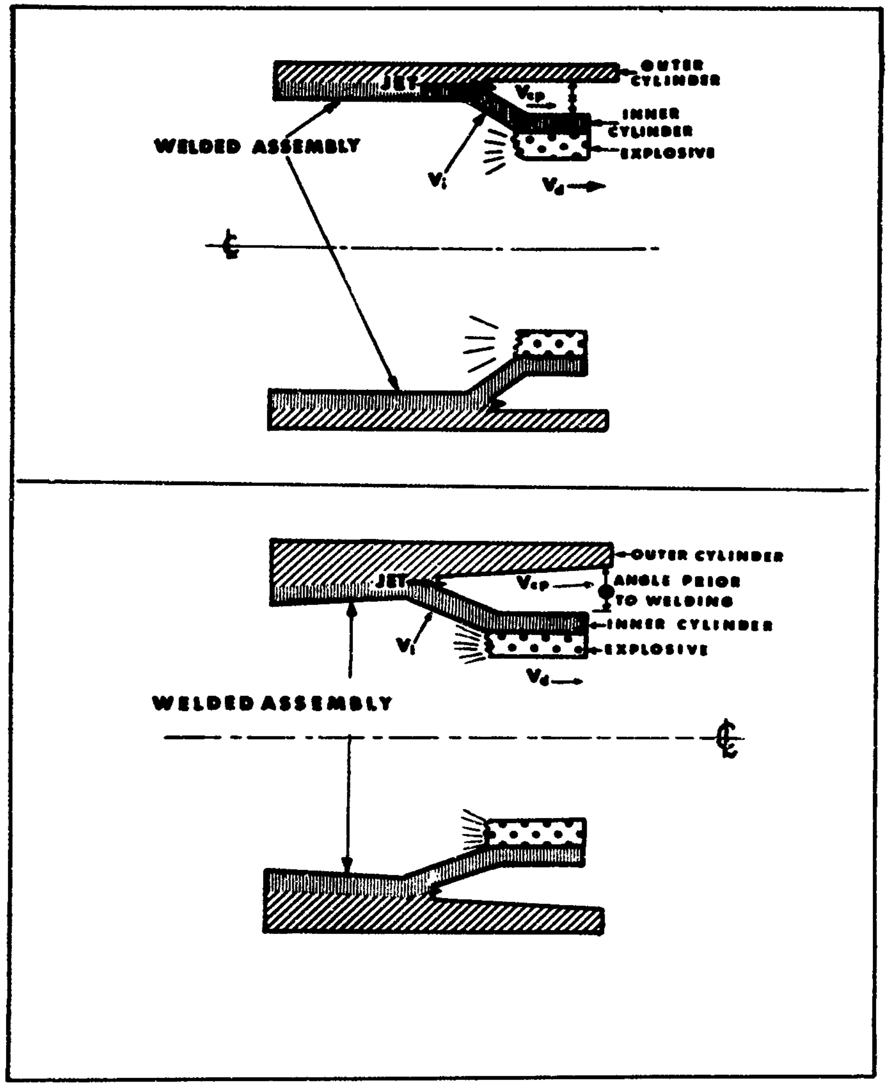

Figure 1. Schematics of Explosive Welding for Cylinders. A (Top): Gap Technique; B (Bottom): Angular Technique.

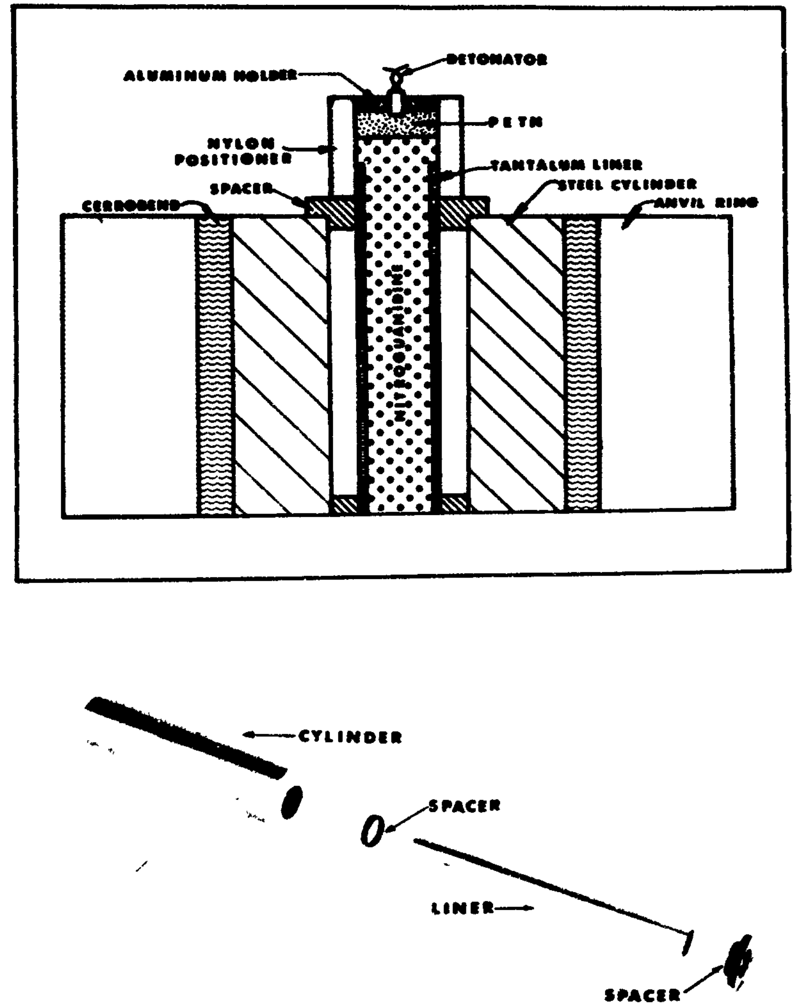

Figure 2. Welding Setup Employing Spacers Between Liner and Cylinder. A (Top): Schematic Drawing; B (Bottom): Photograph of Spacers, Liner and Cylinder

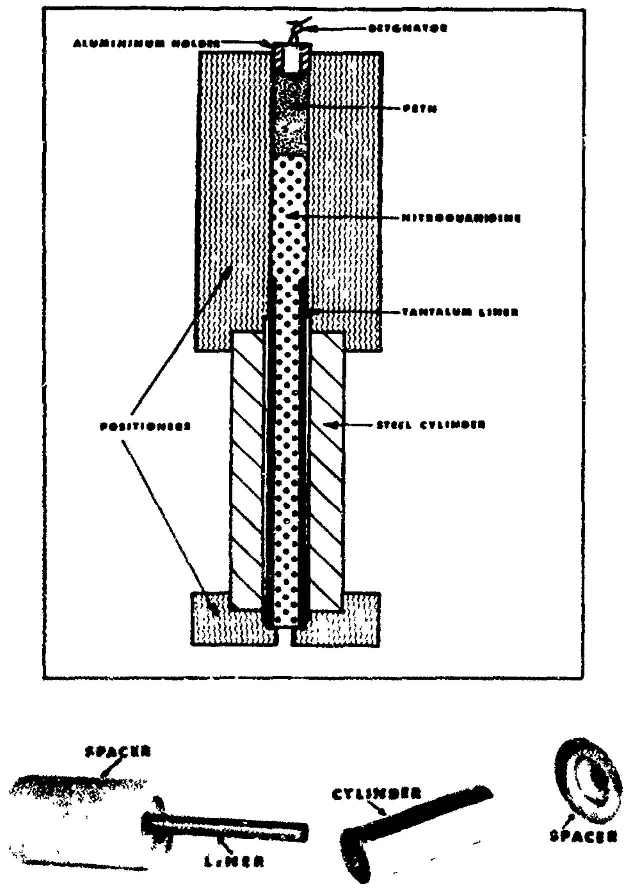

Figure 3. Welding Setup Employ'ng Spacers Outside Liner and Cylinder. A (Top): Schematic Drawing; B (Bottom): Photograph of Spacers, Liner and Cylinder.

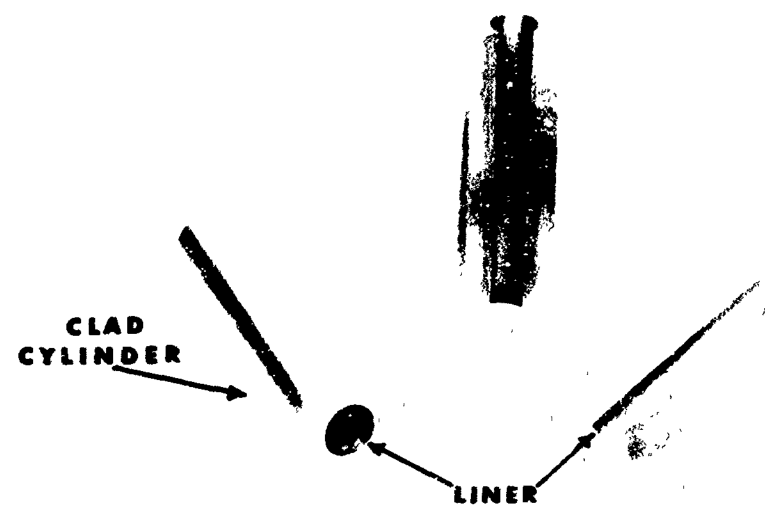

Figure 4. Hollow Steel Cylinders With Interiors Explosively Clad With Tantalum Alloy Liners.

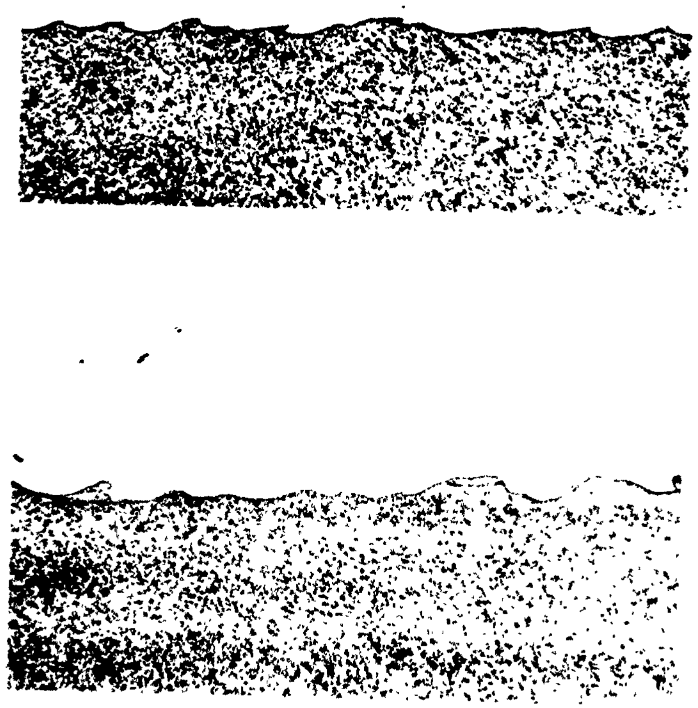

Figure 5. Microstructure of Weld Interface Between 90 Ta-8W-2Hf Tantalum Alloy Liner Clad to Chrome-Moly-Vanadium Steel Cylinder. A (Top): Area Exhibiting Relatively Slight Layer Formation; B (Bottom): Area Exhibiting Heavy Layer Formation.

Mag. - 500X
Etchant - Picral

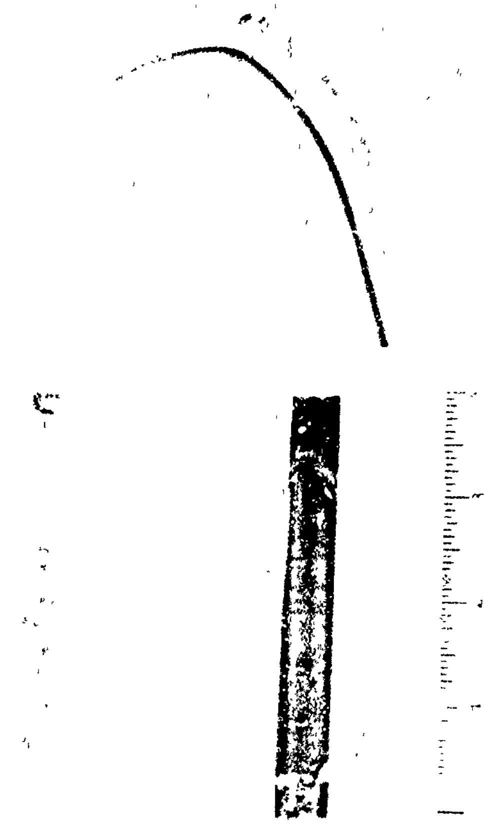

Figure 6 Test Specimens Showing Integrity of Explosion Welded Joints A (Top): Bend Test Specimen, Mag. - 10X; B (Bottom): Peel Test Specimens.

Figure 7. Explosion Welded Tube to Tubeplate Specimen[4].

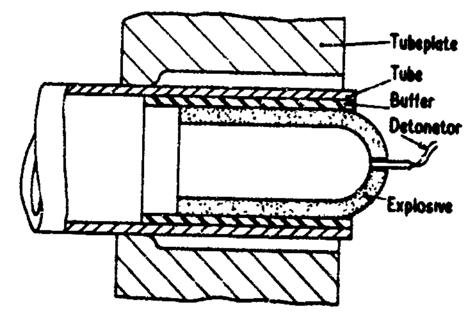

Figure 8 Schematic for Explosion Welding Tube to Tubeplate Using Subsonic Detonation Rate Explosive[4].

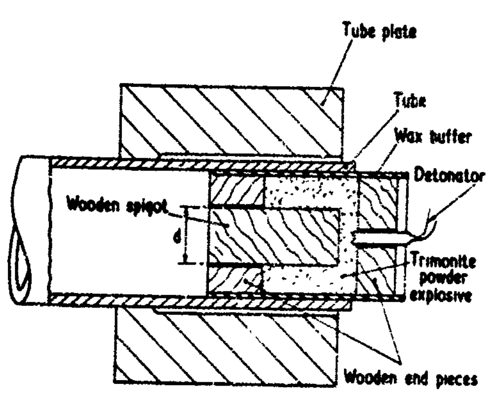

Figure 9 Explosive Pack for Individually Welding Tube to Tubeplate[4].

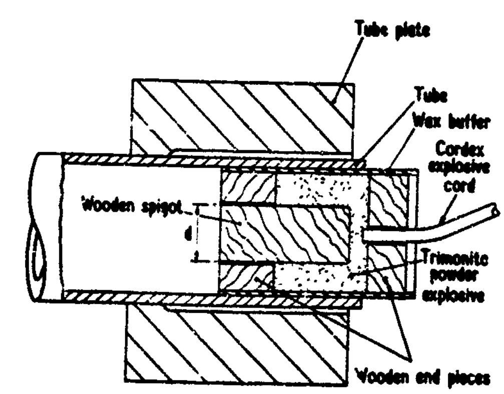

Figure 10. Explosive Pack for Simultaneously Welding a Number of Tubes to Tubeplate[4].

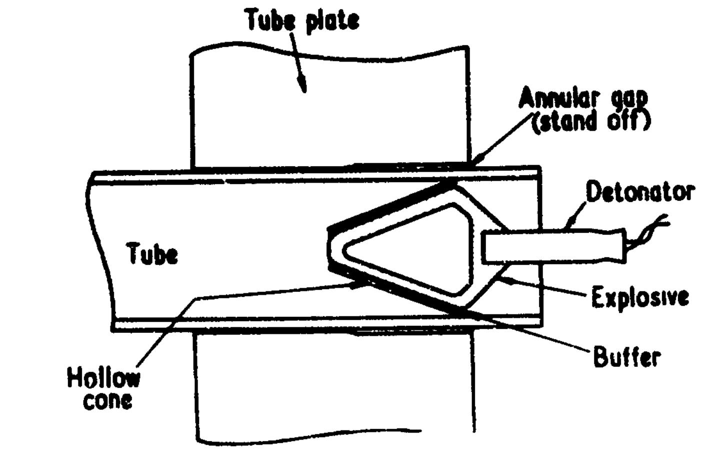

Figure 11. Schematic for Explosion Welding Tube to Tubeplate Using a Supersonic Detonation Rate Explosive and Hollow Cone[3].

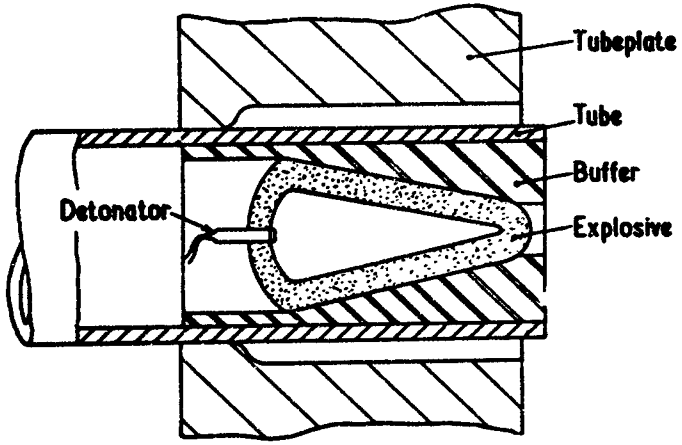

Figure 12. Schematic for Explosion Welding Tube to Tubeplate Using a Supersonic Detonation Rate Explosive and a Tapered Buffer[4].

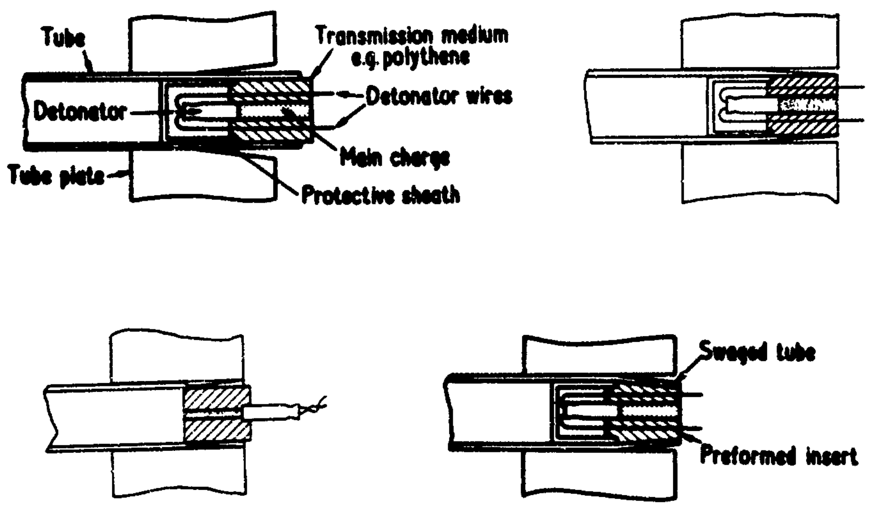

Figure 13. Schematic for Explosion Welding Tube to Tubeplate Using a Angular Technique With Supersonic Detonation Rate Explosive. A (Top Left): Tapered Tubeplate[3]; B (Top Right): Tapered Outer Surface of Tubing and Internal Detonator[4]; C (Bottom Left): Tapered Outer Surface of Tubing With External Detonator[4]; D (Bottom Right): Swaged Tubing[3].

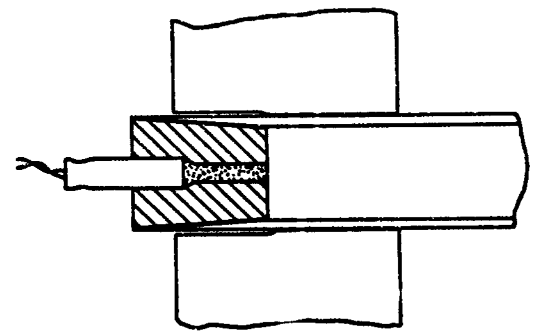

Figure 14. Schematic for Explosion Welding Tube to Tubeplate Using a Supersonic Detonation Rate Explosive and a Tapered Inner Surface on Tube[4].

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13. ABSTRACT

A number of papers have been published in the open literature on the explosion wel[illegible] cylinders and on the joining of tubes to tubeplates. This paper attempts to provide a concise review of these contributions by discussing work performed by the authors and other investigators.

Basically, two explosion welding techniques have been employed to weld cylindrical members. These are the gap technique in which the walls of the members are positioned parallel to each other, and the angular technique in which the walls are inclined at an angle. In the present stage of process development, concentric cylinders generally are welded using the gap technique. Welding conditions and difficulties characteristic of the process are discussed.

Much of the available data on the explosion welding of cylindrical configurations relate to the joining of tubes to tubeplates. Both angular and gap techniques have been used for these applications. Advantages and disadvantages of these techniques are considered and a number of shortcomings that have been encountered are discussed. Various base metal combinations that have been used in explosively welded cylindrical specimens and tubes to tubeplate are reported.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Cladding						
Shaped Charges						
Heat Exchangers						
Tube Plates						
Alloys						
Cylinders, Concentric						
Tubes						

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